COMPARATIVE ANALYSIS BETWEEN LNG IMPORT AND EXPORT TERMINALS

A Thesis

by

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ABSTRACT

According to the US Energy Information Administration (EIA), the natural gas consumption in the US was 1,726 billion cubic feet in January 2013, and the demand has been increasing rapidly around the world as natural gas becomes the fuel of choice for electric power providers. In order to supply this demand, the US economic interest was focused on the Liquefied Natural Gas (LNG) import terminals installation. However, since 2009, due to dramatic changes in gas production and economy the US has become a net exporter of natural gas.

The interest for minimizing the negative consequences associated with LNG terminals has emerged by focusing on the potential damages that may be generated by the flammable and cryogenic characteristics of LNG such as vapor cloud, flash fires, and pool fires.

LNG research and regulation have been successfully applied for providing safer conditions at the LNG import terminals. However, the integration of export terminals into the existing LNG network requires a thorough revision of the new challenges imposed by the specific conditions related to the liquefaction facilities.

It is intended to determine the exclusion zones for these two particular scenarios through the utilization of PHAST in order to estimate the areas where people, property, or the environment would be more severely affected. A revision about the parameters proposed by the normativity for the estimation of the exclusion zones, in contrast to the particular conditions that might affect the plants located on coastal areas is performed.

Additionally, this project seeks to integrate the predicted consequences into real world scenarios by including the implementation of a Geographic Information System (GIS). The georeferenced data will to identify the potential vulnerable areas located near to the LNG facilities.

The main goal intended in this project by the combination of these two computational tools (PHAST model and GIS) is to reduce the gap between the consequence estimation of LNG catastrophic events and the incorporation of these results in a real world environment.

DEDICATION

To my parents: Guido Alberto Lamus and Melba Aurora Gualdron, for being my biggest inspiration through this journey. None of these would have been possible without their incommensurable love and support.

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NOMENCLATURE

BOG	Boiloff Gas
DOT	Department of Transportation
FERC	Federal Energy Regulatory Commission
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MR	Mixed Refrigerant
NFPA	National Fire Protection Association

TABLE OF CONTENTS

	Page
ABSTRACT	ii
DEDICATION	iv
ACKNOWLEDGEMENTS	v
NOMENCLATURE	vi
TABLE OF CONTENTS	vii
LIST OF FIGURES	ix
LIST OF TABLES	x
1. INTRODUCTION	1
1.1 LNG history	1
1.2 Global energy market	2
1.3 US LNG history	3
1.4 US LNG infrastructure	5
2. LNG BACKGROUND	9
2.1 Natural gas	9
2.2 LNG properties	10
2.3 LNG hazards	11
2.4 LNG incident history	13
2.5 Safety regulations for LNG onshore terminals	16
2.6 Evolution of LNG regulations	18
2.7 Vapor dispersion exclusion zones	19
3. ONSHORE LNG TERMINALS	21
3.1 LNG plants	21
3.2 LNG process	21
3.3 Integration of liquefaction trains	24

Page

4. CONSEQUENCE ANALYSIS 28

4.1 Vapor-gas hazard exclusion zone determination................................ 28
4.2 Defining spill scenarios 28
4.3 Prescriptive leak size definition 29
4.4 Leak size definition 30
4.5 FERC approved models 31

5. PROBLEM STATEMENT 34

5.1 Motivation 34
5.2 Objective 35

6. METHODOLOGY 37

7. RESULTS AND DISCUSSIONS 40

7.1 NFPA 59A based simulation 40
7.2 Location based simulation 47
7.3 Results representation on GIS 51

8. CONCLUSIONS 56

8.1 Conclusions 56
8.2 Future work 57

REFERENCES 58

LIST OF FIGURES

Page

Figure 1 Proposed research methodology 37

Figure 2 LNG dispersion 41

Figure 3 Dispersion parameters comparison (Methane) 45

Figure 4 Dispersion parameters comparison (CO2) 45

Figure 5 Dispersion parameters comparison (Propane) 46

Figure 6 Dispersion parameters comparison (Mixed Refrigerant) 46

Figure 7 Dispersion location parameters comparison (Methane) 49

Figure 8 Dispersion location parameters comparison (CO2) 49

Figure 9 Dispersion location parameters comparison (Propane) 50

Figure 10 Dispersion location parameters comparison (Mixed Refrigerant) 50

Figure 11 Approved LNG export terminals 51

Figure 12 Natural gas consumption-production by state 52

Figure 13 Interstate natural gas pipeline network 52

Figure 14 Accidents 2015 interstate natural gas pipeline network 53

Figure 15 Cove Point, Maryland LNG terminal 53

Figure 16 Cove Point dispersion analysis 54

Figure 17 Sabine Pass dispersion analysis 54

LIST OF TABLES

Page

Table 1 LNG modeling parameters 20

Table 2 NFPA 59A parameters 38

Table 3 Materials analyzed 38

Table 4 Release scenarios 41

Table 5 Release scenarios (LNG, CO2) 42

Table 6 Release scenarios (Propane) 43

Table 7 Release scenarios (MR) 44

Table 8 Location parameters 47

Table 9 Release scenarios based on location 48

1. INTRODUCTION

1.1 LNG history

Historical evidence suggests that natural gas was used in China in AD 100 for the extraction of salt from saltwater. The production of salt was required for the preservation of alimentary products and leather processing.

In more recent history, when oil drilling started to gain popularity, gas was found in some wells. In these cases, the wells were abandoned due to the absence of oil. At that time the natural gas was considered unusable, and also was seen as a dangerous substance with unpredictable and unsteady characteristics. On the other hand, the manufactured gas started its development around the same time during the early 1800's.

In contrast to the natural gas, manufactured gas was recognized as predictable, containable, and able to cover the demand where it was needed without the negative implications derived from transportation issues.

However, the manufactured gas high production cost represented a major obstacle that restrained the growth of this industry. In a parallel case, the oil industry continued its consolidation throughout the second half of the 1800's.This scenario enhanced the applicability of the previously assumed waste product, natural gas, for the boilers that were used on the drilling and pumping oil operations.

Due to the cheap price of natural gas, the coal that had been used for operating the pump engines was relegated to a secondary position. Around the 1880's a substantial number of companies located in Pennsylvania began to replace the use of coal for natural gas in the production of pottery, iron, and glass. About a hundred wells were drilled in the Appalachian region in order to provide gas for domestic and industrial uses, and a pipeline for distributing gas to Pittsburgh on an extensive scale was built.

The natural gas industry continued with its development by addressing three major aspects such as production, delivery, and distribution systems. Influenced by the industrialization of the United States, the energy demand remained increasing during this period.

In the year of 1940, Howell Cooper, the president of Hope Natural Gas put in practice a method for storing natural gas in liquid state.

This solution solved the problems related to extensive use of pipelines and large containers. This innovation established the foundations for the modern natural gas industry [1].

1.2 Global energy market

In the year of 2014 a total of 241.1 MT of LNG were traded. This record corresponds to the second largest amount of LNG just behind the post-Fukushima period in 2011 where 241.5 MT were exchanged.

This global LNG market is composed by 19 exporting countries, where eight of them are re-exporting cargoes such as Spain, Singapore, and India. The production of LNG had been concentrated at the Asia Pacific region until the development of the natural gas Qatari industry which has been expanding progressively since the 1990's.

The integration of this new member to the global market has transferred the leading LNG role from the Asia Pacific zone to the Middle East.

According to the world's LNG records, 41% of the global LNG demand was met from the Middle East. There are other developing industries located in the Pacific Basin that have contributed to the market dynamics such as Australia, Malaysia, Brunei and Indonesia.

Additionally, Algeria has strengthened its LNG production by integrating new liquefaction trains. These new trains have increased the process efficiency. On the other hand, 29 countries belong to the group of LNG importers.

The global demand has being led by the Asia and Asia Pacific market which has imported 75% of the global LNG traded. Countries such as Japan and South Korea rely entirely on the LNG imported in order to meet their natural gas demand. In South America, Brazil has increased the importation of LNG as a consequence of severe droughts [3].

1.3 US LNG history

In recent years, the energy demand has been fulfilled mostly by the consumption of fossil fuels such as petroleum, coal, and natural gas. These fossil fuels have covered the 87% of US energy demand during the last decade [2].

During the last century, the United States has exported natural gas via pipeline to Mexico and Canada. The amount of natural gas exported has been less than the imported. The only LNG export terminal of domestic production that has been operating since 1969 is the Kenai LNG Plant located in Alaska which has been exporting liquefied natural gas (LNG) primarily to Japan. By 2000 the U.S. was committed on a consolidation process of supplying the natural gas demand by importing LNG. Forecasting reports presented in 1999 by the Energy Information Administration (EIA) stated that natural gas imports were going to growth from 12.9% to 15.5% for the period of 1997 to 2020 [3]. Based on these reports, five new LNG import terminals were built, and some others existing facilities went through expansion modifications.

However, the abundant production of natural gas during the last decade has changed the economic interests of the American industry. The natural gas profusion has been stimulated by the progress on drilling technologies such as "fracking", which have simplified the extraction process of this natural resource. As a consequence of the rapid growth of domestic natural gas production most of the existing import facilities became unproductive.

According to the most recent forecast studies performed by the EIA, it is expected that by 2016 the US will become in an overall net natural gas exporter. The predictions anticipate that US will be located in third position of largest liquefaction capacity by 2020 after Australia and Qatar [3].

Around 50 permit applications for the construction of new LNG export terminals, or for the modification of existing import terminals have been received by January 2015. Four of the already approved and under construction LNG export projects are oriented to integrate liquefaction facilities to the already existing import terminals, which are known as brownfield projects.

The Federal Energy Regulatory Commission is the agency responsible for approving the permits for these projects by the assessment of the potential damages (societal and environmental) that may derive from the facilities operations [4].

One of the main concerns of the US government is response that will have the domestic gas prices due to the LNG exports. On this regard, the government hasn't imposed ceiling limits on the amount of LNG that will be traded.

1.4 US LNG infrastructure

The LNG infrastructure consists of interrelated facilities that cover the process and transportation of natural gas from the well to the final consumer. Each of these plants, equipment, and transportation modes involve particular challenges related to the specific physical characteristics of the hazardous materials associated with the different stages on the LNG value chain [5].

The three major elements of the LNG infrastructure are: tanker ships, storage tanks, and the terminals.

1.4.1 LNG tanker ships

The transportation of LNG is done by specially designed tanker ships that have large capacities. These tankers are double hulled containing a vast amount of cryogenic tanks. These tanks are sealed and insulated in order to keep the cryogenic material at low temperatures, and also are designed to prevent any release of hazardous substances during transportation operations.

1.4.2 LNG terminals

The LNG cargoes start and complete the trips at import or export terminals where the LNG is processed, load, and unload.

These facilities have docks, LNG processing trains, storage tanks areas, and the connections to the natural gas pipelines network.

The seven terminals operating around the US are: Everett, Lake Charles, Cove Points, Elba Island, Gulf of Mexico, Peñuelas, and Kenai.

Everett, Massachusetts

This terminal is located by the Mystic River from Boston. The tankers approaching this terminal must go through the Boston Harbor in order to arrive at the unloading dock. This was the first import terminal that started operations in 1971. The terminal is operated by a Belgian company, and provides natural gas to the New England residential consumers as wells as some power producers. During the year 2004, 66 LNG shipments were received in this terminal.

Lake Charles, Louisiana

This terminal is located nine miles from the city of Lake Charles in the Gulf of Mexico. The operations at this terminal started in 1981, and received 59 shipments during 2004. During that year, the capacity of the terminal was expanded and it was available for receiving 175 shipments since the 2006.

Cove Point, Maryland

The terminal is located on the Chesapeake Bay next to the city of Lusby about 60 miles from Washington, DC. The terminal is operated by Dominion Corporation, and started operations in 1978.

Due to low domestic prices, the terminal had to close in 1980. Seventeen years later the terminal reopened to liquefy, store, and distribute natural gas to the domestic consumers. Import activities were reestablished by 2003 and 77 LNG shipments were received in 2004.

Elba Island, Georgia

The facility is located on a marsh island five miles from Savanna in Georgia by the Savannah river. The initial operations were established in 1978, and stopped by 1980. In about 2001 the terminal returned to operations. In 2004 the terminal received 41 LNG shipments. The terminal was expanded and the storage capacity increased to 118 shipments per year.

Gulf of Mexico, Louisiana

The terminal was built in 2004 and by 2005 the first LNG shipment was received. This terminal has an offshore gas pipeline buoy system. This buoy system receives the shipment from special ships that regasify their cargoes on board. The expected capacity in 2006 was 60 LNG shipments per year.

Peñuelas, Puerto Rico

The terminal located by the south coast of the island started production in 2002. The facility is responsible for 20% of Puerto Rico’s electric power generation. EcoElectrica owns both the terminal and the electric power plant and by 2004 the terminal received 14 LNG shipments in 2004.

Kenai, Alaska

The facility was completed by 1969, and is the oldest LNG export terminal in the US. This facility was built for exporting LNG to Japan. The plant is owned by Phillips Petroleum and Marathon Oil, and is located near the Cook Inlet gas fields close to the city of Nikiski. The average production rate since 1969 has been 34 LNG shipments per year.

On the other hand, there are some offshore terminals that are connected by underwater pipelines to land. An advantage of the offshore terminals is the fact that it does not represent risks to the public because they are located far from land. As result, this type of plants would lead to fewer negative consequences than those related to onshore facilities.

One of the potential damages of offshore terminals is environmental damage. The facility uses sea water for regasification process, and the water may generate negative effects on the surrounding ecosystem due to the lower temperatures.

2. LNG BACKGROUND

2.1 Natural gas

The main component of natural gas is methane with a combination of other hydrocarbons such as ethane, propane, butane, pentanes, and heavier hydrocarbons. Natural gas is classified as conventional or unconventional according to the rock type where it is found and the trapping mechanism.

Conventional gas is found in very porous formations that can be drilled vertically allowing the flow of gas to the surface. Oil is usually found in these types of wells. The natural gas extracted from these reservoirs contains liquids, and other components that must be processed in order to isolate the natural gas from liquids and contaminants.

On the other hand, the unconventional natural gas deposits are characterized by lower resource concentration and large areas. These types of deposits require well stimulation such as hydraulic fracturing (HF) in order to extract the natural gas. The natural gas that is trapped in an impermeable rock that prohibits its flow and subsequent formation of a conventional gas deposit is classified as unconventional gas. Some of the unconventional gas classifications are shale gas, tight gas, coal bed methane, and methane hydrates. Shale gas and tight gas are commonly found at a distance of two kilometers or more. Hydraulic fracturing, which is the process of pumping fluid into the geologic formations in order to increase the rock permeability is required for the gas production from these deposits.

2.2 LNG properties

The properties of LNG fluctuate depending on the extraction location of the original gas. The composition of the natural gas may include water vapor, carbon dioxide, nitrogen, and helium, which must be removed at the liquefaction plant.

Methane's critical point is -82.75 °C which is the reason why it cannot be liquefied at ambient temperature just by pressure. In contrast to liquefied petroleum gas (LPG, propane, and butane) that can be liquefied by pressure at ambient temperatures, methane must be cooled to the boiling point [5].

LNG refers to natural gas in its liquid form at cryogenic conditions. As a liquid, the natural gas reduces its volume in a ratio of 600:1, which is favorable for storage and shipping through long distances by LNG carriers. LNG is manufactured at a liquefaction facility and subsequently returned to its gaseous phase at a regasification plant.

When LNG is spilled, no residues footprint is left behind because it evaporates completely. LNG has an expansion factor of 600, which means that natural gas will reduce its volume by a ratio of 1:600 when cooled. This allows the transportation of natural gas trough far distances by carriers. Natural gas has a molecular weight less than the air. When the LNG is released, the vapor cloud that is created will rise in the environment in contrast to other heavier hydrocarbons that are heavier than air. Heavier hydrocarbons will tend to accumulate at lower zones which make them more difficult to dissipate. In comparison to coal or other liquid hydrocarbons, LNG generates less CO_2 per unit of energy. The flammability limits of vaporized LNG have been estimated as LFL = 5%, and UFL = 15% in an air mixture. LNG vapor air mixture under partially confined or unconfined conditions will not result in detonation. In order to reach a deflagration scenario, a substantial congestion and high ignition energy are required [5].

2.3 LNG hazards

The hazards of LNG can be derived from different sources such as: liquid leaks from pressurized equipment, liquid leaks from storage tanks, storage tank rollover, or vapor plumes produced from evaporating liquid pools. The scenario of a pressurized liquid leak may occur at the processing plants, and at the pipelines that transport the LNG between the storage tanks and the trains (regasification or liquefaction).

Some of the hazards related to the LNG are: radiation burns, overpressure from vapor cloud explosions at highly congested zones, rapid phase transitions, asphyxiation, freeze burns, and tank rollovers [6].

When the LNG is in direct contact with skin, it can cause freeze burns. Also when equipment that is not designed for cryogenic operations is exposed to the low temperatures of the LNG, it can be affected by embrittlement effects. In terms of environmental damage when the LNG is spilled the consequences are minimal. In comparison with crude oil, the LNG does not need remediation for the soils, groundwater, or surfaces waters because it will evaporate and dilute in the air under atmospheric conditions. An evaporating pool is formed when LNG is spilled on land or water, and the vapor cloud will flow driven by the wind.

A flash fire may occur when the vapor cloud generated by the evaporating LNG finds an ignition source. It is unlikely that a flash fire will produce a secondary ignition or that it will burn beyond of the flaming region. A pool fire will be generated when the flash fire burns towards the LNG pool, and a pool fire will be developed.

Based on the experiments that have been carried out in the past for studying the reactivity behavior of the LNG, it has been determined that the vapor cloud in outdoor conditions would only explode if there are highly congested zones. These highly congested zones refer to a large number of obstacles interacting such as pipelines, and other equipment. These types of congested zones are common at the liquefaction facilities.

However, the particular characteristics of LNG regarding its low reactivity are favorable for minimizing the potential outdoor explosions. Additionally, due to the low reactivity characteristics of LNG, it has been determined that detonation explosions are almost impossible to be generated.

As mentioned before, another hazard related to LNG is asphyxiation. LNG has the potential for decreasing the concentration of oxygen in the environment and this will lead to negative effects on humans. The symptoms presented on humans may vary from impaired behavior, nausea and vomiting, or death depending on the degree of oxygen absence.

The type of concentrations capable for creating these adverse conditions might be generated near the spill for an outdoor release. It is very unlikely that the adverse conditions for developing an asphyxiation scenario would develop near to the vapor plume. It is also unlikely that asphyxiation conditions might be produced due to the elevated vapor concentration at occupied indoor spaces. The applicable regulations regarding safety practices at enclosed areas are responsible for minimizing occurrence of an asphyxiation scenario [6].

2.4 LNG incident history

The LNG industry has an outstanding safety record in comparison with other fossil fuel industries. For instance, there have been about 69 firefighters killed in incidents related to Liquefied Petroleum Gas (LPG) during the period of 1945 to 2004. On the other hand, there are no fatalities reported since the beginning of LNG operations in 1941. Three major incidents have occurred in the US since the first facility started production in 1941.

2.4.1 Cleveland, Ohio 1944

In 1939 the first LNG facility (peak-shaving) was built in West Virginia. The second commercial LNG facility was built two years later by the East Ohio Gas Company in Cleveland. This facility operated under safe conditions until the incident occurred in 1944. Due to an attempt for increasing the storage capacity at the facility, a larger tank was constructed.

During the years of the World War II there was not enough stainless steel available for building the tank. This design failure was the root cause for the storage tank mechanical failure, because the material in contact with the cryogenic temperatures of the LNG produced embrittlement damage at the tank’s wall. As a consequence, the LNG spilled and overflowed the dike which was designed for a smaller volume release.

The liquid spilled flowed into the storm sewer systems located near the process area. The LNG contained at the sewer system formed a flammable vapor cloud that filled the adjacent streets and then it ignited.

The outcome of the incident was 128 people killed due to the vapor and pool fire that affected the nearby utility company building, and a contiguous residential area. The incident investigation performed by the US Bureau of Mines concluded that the Cleveland tank design didn’t follow the specifications stated by the regulations. None of the LNG tanks that were erected following the Cleveland incident suffered embrittlement failures [7].

2.4.2 Staten Island, New York 1973

An incident occurred at the peak-shaving plant on Staten Island in February 1973. Employees from the facility identified a potential leak from the storage tank and stopped the operations. The content from the tank was emptied, and small pieces of mylar lining were found on the tank.

During the tank rehabilitation, the mylar liner and the polyurethane tank insulation were ignited. As a consequence, the temperature increased in the tank, and substantial pressure was generated to dislodge a 6-inch thick concrete roof. Then the roof fell on the workers, and killed 40 of them.

The subsequent investigation reported the event as a construction circumstance and not as a LNG incident.

2.4.3 Cove Point, Maryland 1979

An explosion at one of the electrical stations from the Cove Point LNG terminal occurred in 1979. Due to an inadequately tightened conduit seal from a LNG pump, LNG leaked and entered the electrical substation. There were no gas detectors installed at the electrical station because the scenario of natural gas entering the building was not expected. The flammable mixture was ignited by the electrical ignition sources from a motor control circuit.

The scenario evolved in an explosion that caused the death of one operator in the building, and injuries on a second employee. Additionally, $3 million were lost in terms of economic damage.

The incident investigation determined that the Cove Point Terminal followed the design and construction standards. For this reason the standards were reviewed, and three major design code modifications were integrated [7].

2.4.4 Skikda, Algeria 2004

A steam boiler exploded at the liquefaction terminal in Skikda, Algeria, on the Mediterranean Sea. This explosion led to the release of flammable vapors from a hydrocarbon refrigerant leak into its air intake. A secondary more devastating explosion was triggered and destroyed a considerable area of the plant.

As a consequence of the incident, 27 people died, 74 suffered injuries, and $800 million were lost. The area outside the facility's boundaries reported material damages due to the fire and explosion effects. No damages occurred at the storage tank area. The plant had been operating for over 30 years before the incident with an outstanding safety record.

The sequence of the events previous to the incident started when an operator from the control room detected a rising pressure within the steam boiler. The operator tried to solve the problem by reducing the flow of fuel to the boiler. However, the pressure relief valve was activated. The released flammable material was drawn into the boiler by its air inlet fan.

The explosion occurred when the flammable mixture ignited at the firebox. A flaw in the allocation of equipment led to the incident. The boiler was located near to the area where the gas leaked. The initial explosion generated the failure of a pipe that was transporting refrigerant hydrocarbon. The lack of wind that would have contributed with the dilution of the flammable mixture was one of the contributing factors for this incident [7].

2.5 Safety regulations for LNG onshore terminals

There are two agencies responsible for the regulation of the onshore LNG terminals. These agencies are the Department of Transportation (DOT) and the Federal Energy Regulatory Commission (FERC).

The DOT establishes the safety standards for the onshore facilities involved in LNG processing. The safety standards promulgated by this agency include the 49 CFR 193, “Liquefied Natural Gas Facilities: Federal Safety Standards”. This standard defines the minimal siting requirements, and also includes guidelines from the NFPA for design and construction of LNG facilities. This guidelines look to preserve the integrity of the structures in case of fire, hydraulic forces, and erosion from LNG spills [8]. Other aspects discussed in this standard address operations, maintenance, employee qualification, and security.

As stated by the Natural Gas Act of 1938 (NGA), FERC is the agency responsible for approving the construction of new onshore LNG facilities. FERC has the authority for assessing and approving the siting, construction, and operation of new LNG facilities. Also this agency regulates the existing facilities that are planning to be modified or extended.

Some of the FERC regulations indicate the requirements related to detailed site engineering and design information that support the facility availability for performing LNG processing under safe conditions. FERC is commissioned for evaluating the facility’s proposed location. Another function of this regulatory agency is related to assessing the environmental impacts that might be derived from the LNG facility. Within the environmental assessment some aspects such as facility effects on air and noise quality, public safety in case of an incident or malfunction, socioeconomic impact, safeguards, and geophysical features of the place are considered.

An organization that plays an important role for the LNG regulation is the National Fire Protection Association (NFPA). This is an international organization that is focused on the creation of fire prevention standards. The NFPA 59A:”Standard for the Production, Storage, and Handling of Liquefied Natural Gas” establishes the requirements related to siting, design, construction, fire protection, and safety [9].

2.6 Evolution of LNG regulations

The increasing domestic natural gas production has driven the shift in the US gas industry from being an LNG importer to become a net LNG exporter. For this reason, many companies are trying to implement liquefaction trains at existing LNG import terminals.

The regulations for siting, design, construction and operation of LNG plants are established by 49 CFR 193 and NFPA 59A, where the exclusion zones requirements are specified. The interpretation of the regulations has been clarified by FERC through formal letters. The regulation interpretation has been evolving through the years, and new computational tools have been created in order to cover the requirements of the regulations.

The standards that need to be followed in order to receive the permission by FERC are:

- 40 CFR 68 – Chemical Accident Prevention Provisions.
- 49 CFR 193 – Liquefied Natural Gas Facilities: Federal Safety Standards.
- NFPA 59A- Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG).

These standards require the existence of exclusion zones between the LNG and refrigerant storage units, processing trains, and transfer areas in order to isolate them from probable ignition sources and out of boundary areas. In order to comply with the siting requirements established under 49 CFR 193, the facility design must ensure that the hazardous zone must not extend beyond the boundary limits [10].

It is established by the regulation that a ½ LFL flammable vapor cloud will not trespass beyond the property line for a worst-case release scenario with a 10 minutes time span.

The cases covered are:

- Worst-case loss of containment of LNG or refrigerant (spill).
- Worst-case loss of containment of LNG or refrigerant (jetting and flashing release).

Additionally, an offsite consequence analysis assessing 1 psi overpressure as resulting from the ignition of worst-case 10 min releases is required. Also, a limit of 1,600 Btu/hr/ft^2 (5,000 W/m^2) must not be exceeded beyond the facility's boundary as consequence of a pool fire.

These hazards scenarios are all based on a time span of 10 minutes for releases of LNG or flammable refrigerants at the maximum leak flow rate, following the scenarios established by FERC for pipe break.

2.7 Vapor dispersion exclusion zones

The US regulation 49CFR193.2059 for LNG terminals establishes the identification of exclusion zones for each LNG container and transfer system in order to protect the population located nearby.

The exclusion zone is calculated by determining the distance to the ½ lower flammability limit (LFL) from the downwind edge of the impoundment. As mentioned before, the flammability range of LNG goes from 5% to 15%. Therefore the contour of the exclusion zone is defined as 2.5% flammable material in the air.

Regarding the parameters used by the approved models for determining the exclusion zones, the software must incorporate ambient conditions such the atmospheric stability, the wind speed at 10 m, relative humidity, and surface roughness.

Table 1. LNG modeling parameters

Parameter	Value
Atmospheric stability class	F
Wind speed	2.0 m/s
Relative humidity	0.5
Surface roughness	0.03m

In case that the surrounding terrain next to the source has dense vegetation, a different roughness parameter may be used. Additionally, a different set of temperatures might be used when it is checked that these new temperatures produce larger distances in 90% of the time.

3. ONSHORE LNG TERMINALS

3.1 LNG plants

The natural gas facilities are responsible for processing associated and nonassociated gas in order to produce LNG. The quality of the natural gas produced is determined by the market specifications. There are several different processes performed at the natural gas facilities such as:

Dehydration of gas helps to minimize corrosion, also to prevent the formation of clogs at the pipelines when the materials are under cryogenic conditions. Carbon dioxide is separated from the natural gas. In order to minimize the environmental damage, this carbon dioxide can be reinjected into the reservoirs. When processing natural gas it is required to remove impurities such as H_2S in order to make it marketable.

Liquefaction processing is done for producing the merchandisable liquid output or for storing purposes. The natural gas is liquefied in order to allow the product to be transported to distant markets. It is common to find these types of facilities located near to large gas reservoirs. The first LNG liquefaction facility with exporting capacity was the Kenai facility located in Alaska.

3.2 LNG process

3.2.1 Field operations and inlet receiving

The gas processing facilities in most of the cases are interconnected through a pipeline network to the field operations. These pipelines provide the raw natural gas to be processed at the plant. Some processes included in the field operations are measurement, liquid separation, dehydration, removal of carbon dioxide and hydrogen sulfide, and compression. Usually the gas received at the plant comes with residues and impurities that must be removed at the initial stage of the facility processing.

3.2.2 Inlet compression

It is common to find inlet compression at the natural gas facilities, although in some cases the inlet compression might be unnecessary when the inlet streams have pressures around the 700 psi. Usually the facilities use a similar type of compressors for the inlet, field and outlet activities. Among the energy consumption sources at a gas plant, this one represents the major source for energy expenditure [11].

3.2.3 Gas treating

At this stage acid gases (Hydrogen sulfide and carbon dioxide) along with other sulfur pollutants are treated for removal. Water based absorbents are usually used by most of the gas processing facilities for removing the impurities; however other solvents and processes might be also used.

3.2.4 Dehydration

In order to avoid the clogs that might be generated from the gas hydrates, it is required to dry the gas. This process also contributes by minimizing the corrosion effects. The plants that use water based treating require dehydrating the gas. Usually the gas received at the inlet pipeline contains water excess. Before starting the cryogenic process, the water must be eliminated because under low temperatures it can freeze and that would represent a critical problem for the pipelines.

3.2.5 Hydrocarbon recovery

At this stage in the process, the hydrocarbons are separated. Some of the hydrocarbons recovered are used as fuel in the plant and some other are commercialized. The mixture of natural gas received at the inlet pipeline may contain different concentration of methane and heavier hydrocarbons that require to be separated.

3.2.6 Trace components

The mixture from the raw natural gas includes a combination of impurities that are required to be removed in order to reach the costumer specifications. These impurities come in low concentrations but without the adequate processing the final product would be rejected by the buyer. One of the substances that must be removed is mercury because it can generate mechanical failure in the aluminum heat exchangers.

3.2.7 Outlet compression

Most of the natural gas facilities use turboexpanders for the refrigeration process and also for compressing the gas that is sent to the through the pipelines. A portion of the work used for recompressing the residue or sales gas comes from the expansion process.

3.2.8 Liquid processing

The natural gas adopts its gaseous state when processed at the liquefaction train. The liquefaction process takes into account the specific properties of the received raw material, and the final consumer expectations for the product [11].

3.2.9 Sulfur recovery

The ways for disposing the H2S removed from the natural gas depend on the amounts of the toxic material and they are: flaring, elemental sulfur conversion, and well reinjection. The easiest way to dispose the hydrogen sulfide is by flaring the excess amount. However, when the levels of H_2S are higher than the emission limits, it should be considered to use the conversion of the material into elemental sulfur, or reinject it at the well for disposal [11].

3.3 Integration of liquefaction trains

3.3.1 Key elements from facility modification

The rising natural gas domestic production has created new opportunities for exporting LNG. As a result of this situation, the established LNG import companies have shown their interest for integrating liquefaction trains into their existing regasification facilities.

The benefit for integrating liquefaction equipment into the previously built plant lies on the possibility for using available infrastructure such as storage tanks, docks, as well as processing expertise, license and market contacts.

However the integration of liquefaction process equipment provides additional hazards that must be thoroughly assessed in order to minimize the potential negative outcomes.

Some of the major units that must be installed related to the liquefaction train are:

- Compressors for feed gas and refrigerant.
- Heat exchangers for precooling feed gas (air or water cooled).
- Main cryogenic heat exchanger.
- Hydrocarbon fractionation units.
- Additionally spill containment systems.
- Extra electrical power distribution system.
- Increase the capacity of the firewater systems.

The main hazards considered for the integration of the liquefaction process in an existing LNG import facility are:

- LNG hazards (common for import and export).
- Hazards related to the use of hydrocarbon refrigerant, and impurities of natural gas received from the inlet pipeline.

Some of the hazards and design requirements are common to both types of facilities (import and export). These hazards are associated with the length of the pipeline, and flow rate conditions. When converting the unidirectional flow at the import terminals into a bidirectional one, it is common to keep the same flow rate that had been used. On the other hand, a significant modification related to the spill containment barriers may need to be done. An extended spill containment system must be integrated between the liquefaction train and the storage tank area.

An updated vapor dispersion analysis must be performed in order to evaluate the potential scenarios that would be generated by the integration of other hazardous materials (hydrocarbon refrigerants).

It is required to evaluate and propose updated designs for the overall spill sumps containment capacity in order to ensure that the additional chemical compounds would be properly contained in case of an incident.

A different set of materials such as refrigerant hydrocarbons, as well as raw natural gas will capture the attention when rerunning the consequence hazard analysis. For instance, the vapor dispersion from refrigerants must be identified. Additional gas detectors must be installed in order to protect the zones that might be affected by flammable vapor clouds.

3.3.2 Vapor handling system

Modifications regarding vapor handling system must be performed. In the case of an import terminal, the compressed gas generated at the boiloff gas is usually sent towards the sendout pipeline. On the other hand, for the export terminals the boiloff gas is used as part of the facility's fuel gas system after it is compressed. One of the main concerns at the liquefaction plants is to increase the efficiency of the process by limiting the generation of BOG. The production of BOG in the liquefaction train must be analyzed during the design stage by taking into account the pressure conditions for the storage tanks and process vessels. In order to reduce the generation of BOG, the process must keep subcooled conditions that will help to avoid the thermodynamic flash effect [12].

3.3.3 From import to export terminal

Redefining the operations that take place at the existing LNG terminals will represent a series of challenges that must be attended. In case that the number of changes would be elevated, it requires a proportional magnitude of modifications to be reanalyzed. Keeping the safer operational conditions as possible will be the main objective for the modification projects.

Although several existing equipment, protective barriers, storage tanks would be subjected to modifications, a substantial amount of new components might be integrated at the LNG facilities. The implementation of an extended operational and maintenance program must be established for reaching a successful facility performance.

In order to comply with standards, the updated designs for the new LNG export terminals must be thoroughly analyzed. This is a particular scenario where the advantages found on integrating additional processes to an existing facility require the implementation of a thorough safety analysis. Just in that way, it would be possible to ensure that safe and efficient activities would be performed.

4. CONSEQUENCE ANALYSIS

4.1 Vapor-gas hazard exclusion zone determination

The federal regulation 49 CFR 193 establishes that any LNG storage tank and transfer system located within an LNG plant must have an exclusion zone defined by vapor dispersion analysis which are defined by following the prescriptive guidelines contained in sections 2.2.3.3 and 2.2.3.4 of NFPA 59A.

It is specified by the 49 CFR 193 that the exclusion zones must be “an area surrounding an LNG facility in which an operator or government agency legally controls all activities in accordance with §193.2057 and §193.2059 for as long as the facility is in operation”.

Based on the exclusion zone regulation description, the facility boundary for which the vapor dispersion exclusion zone would be enforced is delimited by the fence at which the facility operator ceases to control all activities [13].

The hazard exclusion zone cannot prolong beyond the facility boundary limits.

4.2 Defining spill scenarios

According to NFPA 59A, the design spill must be chosen based on single accidental leakage source scenario for the process areas. It is not thoroughly specified what a single accidental leakage source involves by the NFPA 59A; however, a list of some particular scenarios is provided. Therefore, FERC has presented guidance for selecting single accidental liquid leakage sources to assess in order to support that the facility is in agreement with the 49 CFR Part 193.

4.2.1 Types of leaks

The releases of flammable materials such as LNG or refrigerants are divided into two groups by FERC's guidance. Both of these categories must be considered for the analysis of the exclusion zones.

4.2.1.1 Liquid spill scenarios

This scenario considers a full pipe rupture and the consequent liquid spill onto the ground. The liquid is released and collected in the trenches, troughs, and impoundments. Subsequently, the material released evolves in a vapor cloud that disperses in the environment. Then the exclusion zone is defined by the calculated vapor cloud.

4.2.1.2 Pressurized release scenarios

In contrast to the liquid spill scenarios, this scenario considers the releases where no liquid reaches the ground. As these scenarios produce limited or no rainout, they tend to generate vapor clouds that cover larger extensions.

4.3 Prescriptive leak size definition

FERC has defined the types of leak scenarios required for modeling in order to standardize the procedures for assessing single accidental leakage source.

Initially FERC established the assessment of all small diameter attachments related to the transfer pipelines, pressure reliefs, recirculation, and any flanges that are used at valves or other equipment for the estimation of the largest spills.

This approach was supported by the DOT. As a consequence, a vast range of single accidental leakage sources were presented to the FERC by the applicants. Then FERC defined more specific criteria for the selection of leaking sources, for piping between the range of 100 m and 1000 m length. Full-pipe rupture was established at any point along the pipeline for a line equal or less than 6 inches in diameter.

On the other hand, for a pipe with a diameter greater than 6 inches, a hole size of 2 inches in diameter, was established. Additionally, a hole equivalent to 1/3 of the pipe diameter was defined, for piping greater than 12 inches in diameter.

4.4 Leak size definition

No quantitative justification was provided for the selection of design spill on the introductory prescriptive approach for instructing about a single leakage source. Later FERC decided to establish an acceptable failure rate for LNG storage tank outlet line for the definition of a quantitative criterion. It was established by FERC that a tank outlet line would fail every 20,000 to 30,000 years ($5x10^{-5}$ to $3x10^{-5}$ failures per year). According to this, FERC established the selection of accidental leakage sources when the annual likelihood of failure was greater than $3x10^{-5}$.

FERC presented a failure rate set for determining the failure likelihood of the components found at the LNG processing systems in the plants. Some of the equipment that must be considered are: transfer and process equipment, process vessels, valves and joints, transfer arm and hoses.

4.5 FERC approved models

There are different computational tools used for modeling incident releases that have been approved by FERC. These vapor dispersion models have been tested against the Model Evaluation Protocol established by the Fire Protection Research Foundation in 2007.

4.5.1 DEGADIS

According to NFPA 59A Standard for the Protection, Storage, and Handling of Liquefied Natural Gas, the distances reached by the flammable mixture must be calculated by using the Dense Gas Dispersion Model (DEGADIS).

This model has been developed by the Gas Research Institute. The prescription of this model as the tool for calculating exclusion zones was removed in 2009 by the NFPA 59A, and the models were accepted as the approved models under the model evaluation protocol.

This model considers the effects of gravity spreading, negative or positive buoyancy, heat transfer from surface to the cloud, and phase change related to the humidity in the air for dense gas dispersion. The model was developed by the Gas Research Institute in collaboration with the US Coast Guard [13].

4.5.2 PHAST integral model

This model was authorized by PHMSA in 2011 for the analysis of exclusion zones from LNG vapor dispersion. Det Norske Veritas is the company that developed this commercial software. PHAST has been extensively used for determining the hazard distances from the release of a variety of hazardous substances, and LNG is one of them.

The Unified Dispersion Model (UDM) is the code used by PHAST as an integral model for the dispersion calculation. This code follows a two-phase pressurized release, or an unpressurised release. The Unified Model Dispersion allows the calculation for continuous, instantaneous, constant finite duration and general time varying releases. It also allows the calculation when the plume lift-off due to buoyant effects. A large number of experimental data have been used for validating this software [13].

4.5.3 FLACS CFD model

The Model Evaluation Protocol has been used for the validation of FLACS as an LNG vapor dispersion model. Extensive experimental data has been used for validating this tool. The US DOT received a petition in 2010 looking for the approval of this software as an alternative option for LNG vapor dispersion model. By 2011 a final decision from the US DOT was presented where the agency approved the use of FLACS for calculating the dispersion exclusion zone.

Among the capabilities of this commercial software, there are the possibilities for analyzing vapor dispersion and vapor cloud explosion scenarios. The CFD model solves the Navier-Stokes equations for a time dependent input. The model integrates conservation equation for mass, enthalpy, momentum and gas concentration in order to provide results represented in a Cartesian grid for a finite volume.

The software includes liquid spill model that applies the shallow water equation in order to calculate the spread of LNG or hydrocarbons on the ground. Additionally, it has a pool evaporation model that determines the heat transfer from the ground surface, the wind convection effects, and also radiation.

This is the only software that is able to include the effect of obstacles in the modeling of vapor clouds. As a result, the software has been approved for modeling the resulting vapor clouds from spills onto trenches [13].

5. PROBLEM STATEMENT

5.1 Motivation

The rising production of domestic natural gas in the US during the last decade has driven a change regarding the interest for exporting LNG instead of importing it. The importation of LNG was thought as a main supply for the national energy demand until the beginning of the 21st century. However, the increasing domestic production has been stimulated by the development of upstream operations technologies such as hydraulic fracturing which has allowed the extraction of this fossil fuel from the extensive shale gas formations.

Around 50 project applications have been received by requesting permits for operating LNG export facilities. The existing LNG import terminals that were built around the year 2000 have been idle during the last years; for this reason, FERC has had special considerations for granting the permit to these existing facilities in order to start the brownfield project development in the immediate future.

The integration of liquefaction trains within the existing LNG import terminals will represent additional challenges for the entire safe operation. Hazardous hydrocarbon refrigerants that were not included for the import regasification processing, as well as toxic impurities derived from raw natural gas represent an increasing overall potential negative consequence [16].

During the last five years, five import terminals got FERC's permission for construction and operation of export terminals. LNG terminals such as Corpus Christi, Freeport, Sabine Pass, Hackberry and Cove Point have been integrating all the equipment related to the liquefaction trains that will be used for starting export activities in the close future.

As the domestic natural gas production keeps increasing the interest for exporting this fossil fuel, several project proposals are still under revision by FERC. Therefore, studying the parameters established by the NFPA for the calculation of exclusion zones seems as a useful analysis. This analysis allows to get a preliminary idea of how these modify facilities might affect the nearby populations.

Additionally, the results obtained from the modeling stage will be represented through the implementation of Geographic Information System (GIS). The implementation of this computational tool represents an opportunity for contextualize the theoretical results into a real world environment (nearby population density, land use data, gas pipeline network) [17].

5.2 Objective

This research intends to perform a consequence analysis for an LNG terminal including regasification and liquefaction processes. The objectives of this study are:

1) Calculate the flammable vapor dispersion for a set of hazardous materials used in the processing of natural gas at import and export terminals. The set of hazardous materials consists of: methane (liquid and gas), propane (liquid and gas), carbon dioxide (gas), and mixed hydrocarbon refrigerant (liquid and gas).

2) Assess the coastal areas environmental effects related to wind speed and relative humidity that might generate a different kind of results in comparison with those obtained when using the NFPA regulatory parameters.
3) Integrate the results in GIS in order to identify the zones outside the facility's boundary that might be under potential damage.

6. METHODOLOGY

The methodology used for developing this project is explained in the figure 1. In order to estimate the exclusion zones required by the NFPA regulation a set of different materials at different pressure and temperature conditions has been proposed.

The subsequent stage is to evaluate different scenarios by modifying particular environmental conditions that could be found at the locations of the Cove Point, and Sabine Pass LNG terminals. Finally, the results obtained will be integrated into the GIS tool in order to identify the populated zones under potential damage.

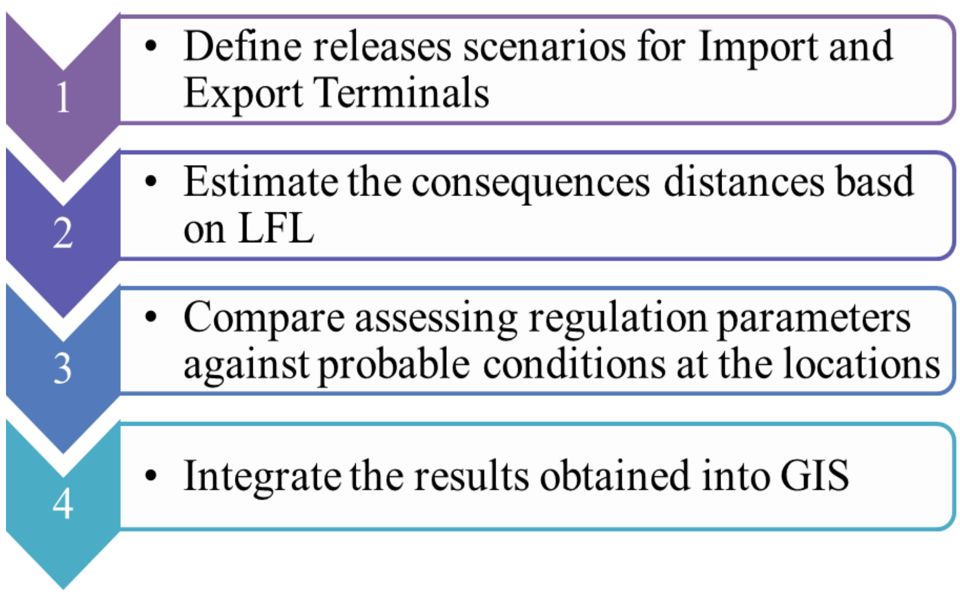

Figure 1. Proposed research methodology

Some of the different hazardous materials that might be found at common regasification and liquefaction terminals were modeled by using PHAST where the NFPA 59A conditions parameters were used.

Table 2. NFPA 59A parameters [9]

Parameter	**Value**
LNG	Methane
Atmospheric stability class	F
Wind speed	2.0 m/s
Relative humidity	0.5
Surface roughness	0.03m
Ambient Temperature	70 °F
Release Duration	10 min
Hole Size (diameter)	0.5” - 2” – 4”

Additionally, for the LNG export terminal the following materials were analyzed

Table 3. Materials analyzed

Material	**State**	**Pressure (psi)**
Methane	Gas	1000
Methane	Liquid	2.7
CO2	Gas	15
Propane	Liquid	220
Propane	Gas	103
MR	Liquid	194
MR	Gas	428

MR represents a mixed refrigerant hydrocarbon material that consists of nitrogen, methane, ethane, propane, and ethylene.

Finally, a parametric analysis has been performed in order to evaluate how much influence can be derived from the parameters atmospheric stability, ambient temperature, and hole diameters.

7. RESULTS AND DISCUSSIONS

The results obtained from the simulation performed by using PHAST are presented in this section. The initial set of data analyzed was based on the parameters established by the NFPA 59A regulation. Two cases were assumed for modeling the conditions found at an LNG import terminal. Additionally five other scenarios were selected for describing the particular conditions at an LNG export terminal.

The simulation was run for a horizontal release at the contiguous pipeline segment from the equipment. For instance, if LNG is being transported by a pump, or propane used as refrigerant passing through a heat exchanger, the releases adopt the process conditions given by the equipment involved.

The released is assumed to happen during a 10min time span.

The results obtained from following the parameters established by the regulation were compared against the worst case scenario proposed by Crowl and Louvar [14]. The authors proposed a wind speed of 1.5 m/s instead the 2.0 m/s identified by the NFPA. Additionally, two different terminal locations were selected (Maryland and Louisiana) in order to check how the specific ambient conditions of two coastal areas located at different latitudes may affect the vapor dispersion calculations.

7.1 NFPA 59A based simulation

The definition of the exclusion zones, required by the regulation, was performed for seven scenarios. These seven scenarios represent the process conditions at a medium size regasification or liquefaction LNG train. Different pressures and temperatures, consistent to the expected materials conditions at each process stage were considered. For instance, when the model required for modeling a release of methane at its liquid stage, the selected modeling temperature was below -256°F.

Table 4. Release scenarios

	Terminal		
Material	Import	Export	State
Methane	x	x	Gas
Methane	x	x	Liquid
CO2		x	Gas
Propane		x	Liquid
Propane		x	Gas
MR		x	Liquid
MR		x	Gas

Figure 2. shows a vapor cloud side view of a Methane release with the identification of the different concentrations.

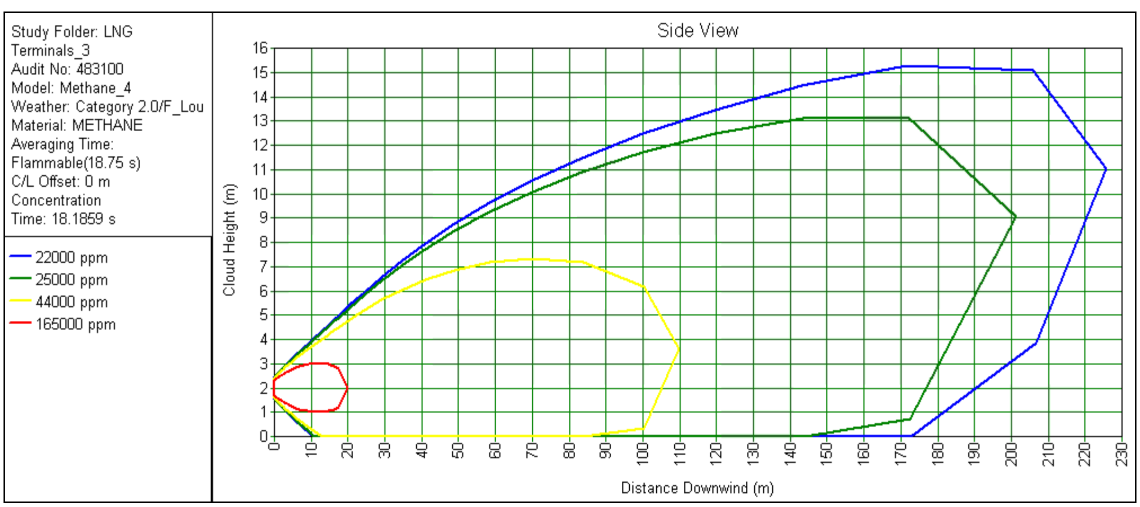

Figure 2. LNG dispersion

The exclusion zone is calculated based on the ½ LFL downwind distances. From the previous figure it can be observed that methane tends to flow upward, and this is consistent with its lighter weight in comparison to air.

Table 5. Release scenarios (LNG, CO2)

Composition	**State**	**Concentration (ppm)**	**Hole size (in)**	**Speed (m/s)**	**Stability Class**	**Distance (m)**
Methane	Gas	2500	0.5	1.5	F	17
				2	F	16.5
				7	D	12
			2	1.5	F	90
				2	F	88
				7	D	72
			4	1.5	F	200
				2	F	200
				7	D	175
Methane	Liquid	2500	0.5	1.5	F	31
				2	F	26
				7	D	8
			2	1.5	F	215
				2	F	196
				7	D	67
			4	1.5	F	460
				2	F	450
				7	D	120
Carbon Dioxide	Gas	5000	0.5	1.5	F	7
				2	F	6.6
				7	D	5
			2	1.5	F	35
				2	F	33
				7	D	15.5
			4	1.5	F	95
				2	F	93
				7	D	64

Table 6. Release scenarios (Propane)

Composition	**State**	**Concentration (ppm)**	**Hole size (in)**	**Wind Speed (m/s)**	**Stability Class**	**Distance (m)**
Propane	Gas	21000	0.5	1.5	F	5.5
				2	F	5.5
				7	D	4.8
			2	1.5	F	22
				2	F	22
				7	D	17
			4	1.5	F	52
				2	F	52
				7	D	46
Propane	Liquid	21000	0.5	1.5	F	4.2
				2	F	4.2
				7	D	3.6
			2	1.5	F	16
				2	F	15.8
				7	D	12.5
			4	1.5	F	36
				2	F	35
				7	D	28

Table 7. Release scenarios (MR)

Composition	State	Concentration (ppm)	Hole size (in)	Wind Speed (m/s)	Stability Class	Distance (m)
Mixed Refrigerant	Gas	31521	0.5	1.5	F	6.5
				2	F	6.5
				7	D	5.7
			2	1.5	F	28
				2	F	27.6
				7	D	22
			4	1.5	F	65
				2	F	65
				7	D	61
Mixed Refrigerant	Liquid	27299	0.5	1.5	F	50
				2	F	49
				7	D	17
			2	1.5	F	320
				2	F	295
				7	D	150
			4	1.5	F	650
				2	F	640
				7	D	310

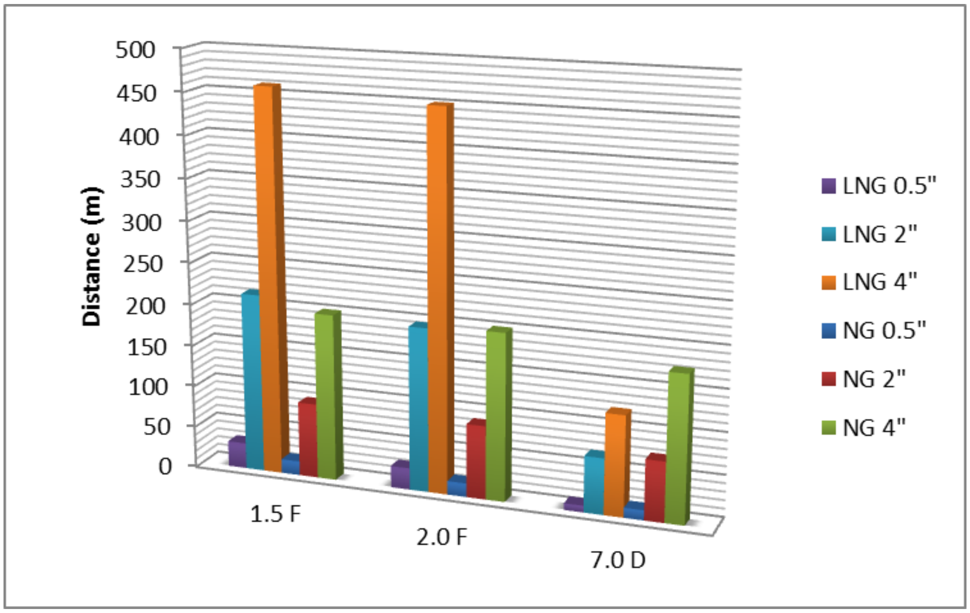

Figure 3. Dispersion parameters comparison (Methane)

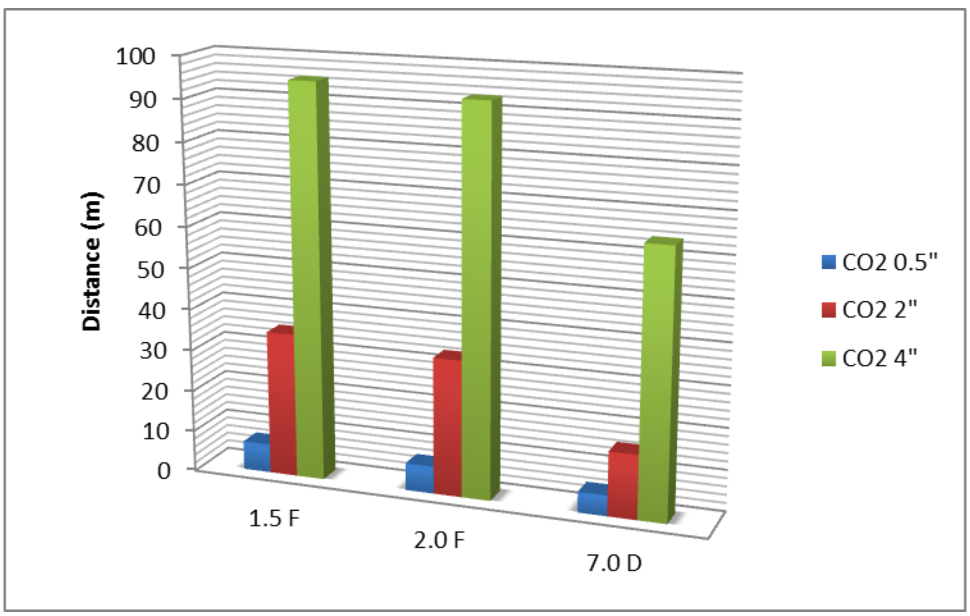

Figure 4. Dispersion parameters comparison (CO2)

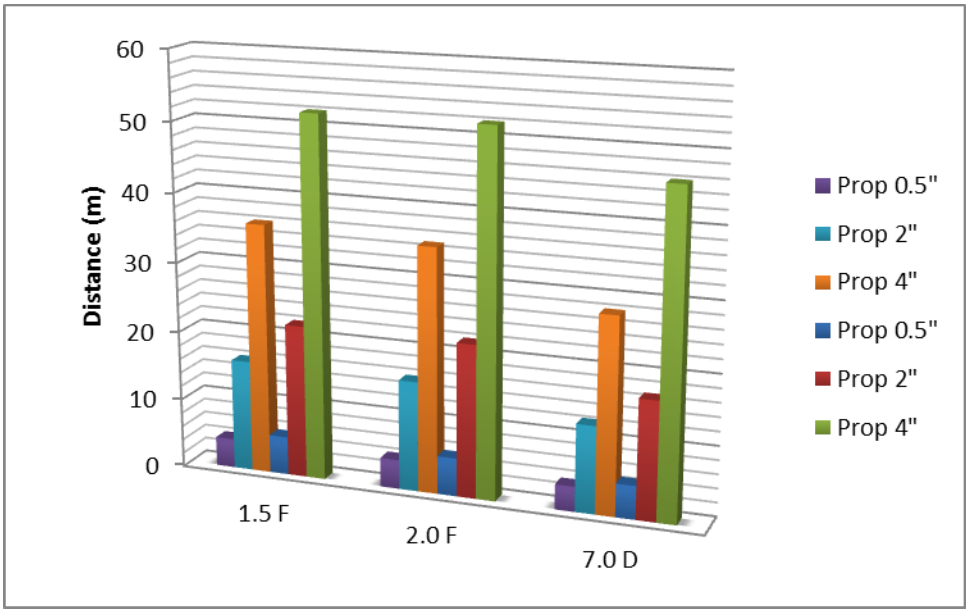

Figure 5. Dispersion parameters comparison (Propane)

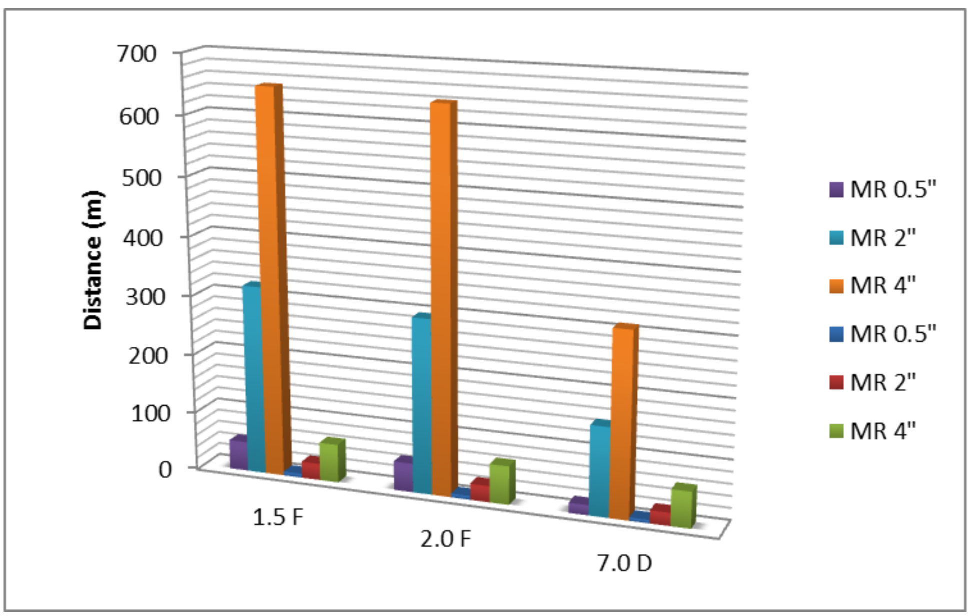

Figure 6. Dispersion parameters comparison (Mixed Refrigerant)

In the bar diagrams we can observe that the difference between NFPA 59A (2.0 F) parameters and the worst case scenario proposed by Crowl and Louvar (1.5 F) is relatively imperceptible [14]. However, when we evaluate the dispersion based on a 7 m/s wind speed and a stability class D that are common for coastal areas, the distance calculated are more severely affected [15].

7.2 Location based simulation

At this stage, the parameters proposed by the NFPA 59A for wind speed (2.0 m/s) and stability class F have been selected. What is intended, is to incorporate the particular ambient conditions for Maryland and Louisiana (relative humidity and ambient temperature) in order to compare how can be affected the dispersion distance by these specific location characteristics.

Table 8. Location parameters

Terminal	**Location**	**Relative Humidity**	**Ambient Temperature (°F)**
Cove Point	Maryland	0.8	57.4
Sabine Pass	Louisiana	0.9	68.5

Table 9. Release scenarios based on location

Composition	State	Con. (ppm)	Hole size (in)	Louisiana	Maryland
Methane	Gas	2500	0.5	16.5	16.5
			2	95	95
			4	200	210
Methane	Liquid	2500	0.5	24	22
			2	195	205
			4	380	400
Carbon Dioxide	Gas	30000	0.5	1.6	1.5
			2	6	6
			4	12	12
Carbon Dioxide	Gas	50000	0.5	1	0.9
			2	3.5	3.5
			4	7.5	7
Propane	Liquid	21000	0.5	5.5	5.5
			2	22	22
			4	52	51
Propane	Gas	21000	0.5	4.1	4.1
			2	15.9	15.5
			4	36	35
Mixed Refrigerant	Gas	31521	0.5	6.6	6.6
			2	27	27
			4	65	65
Mixed Refrigerant	Liquid	27299	0.5	46	46
			2	295	290
			4	649	625

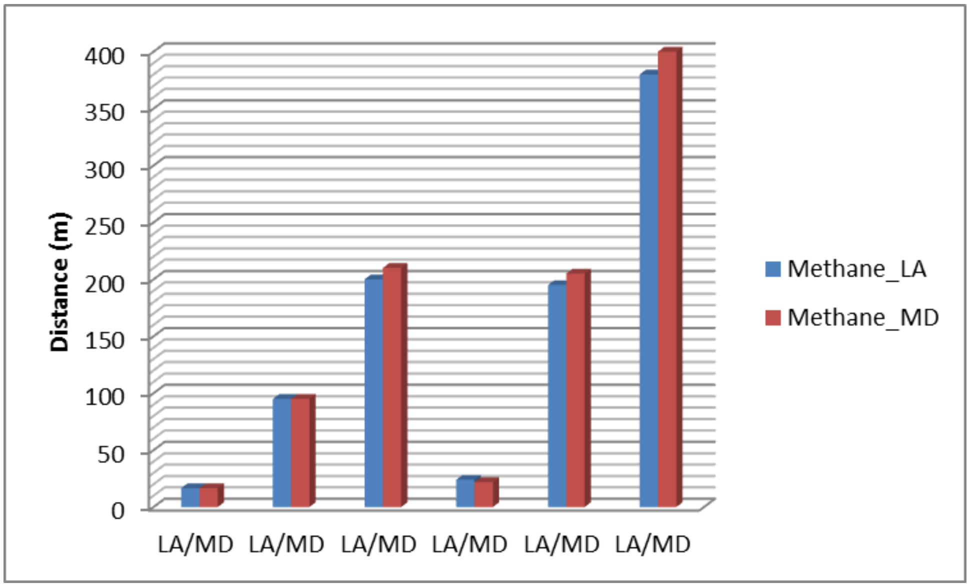

Figure 7. Dispersion location parameters comparison (Methane)

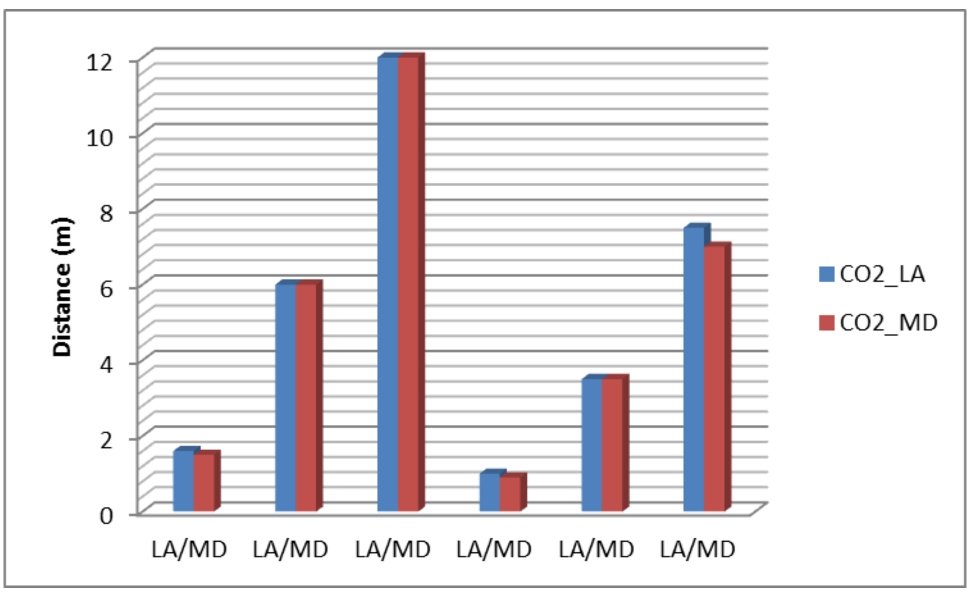

Figure 8. Dispersion location parameters comparison (CO2)

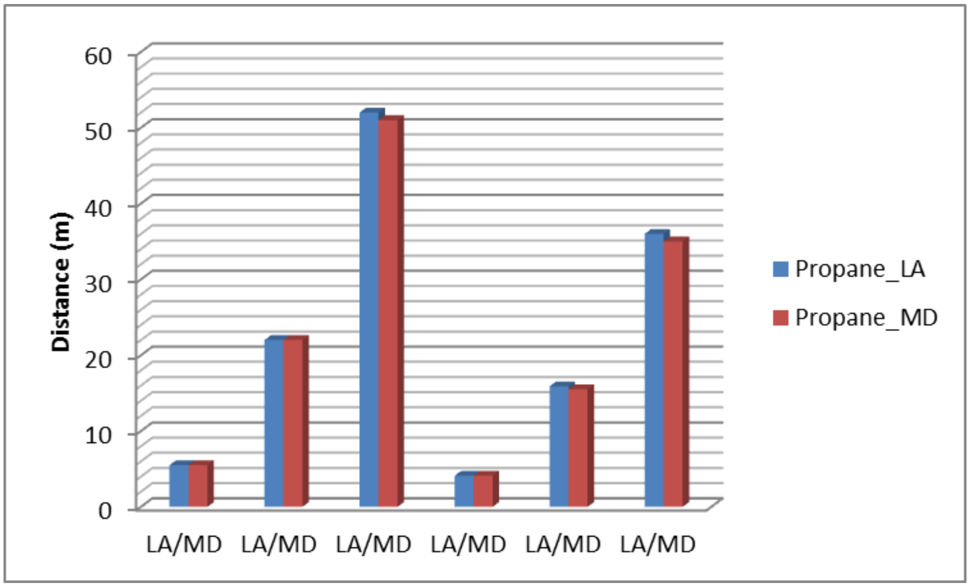

Figure 9. Dispersion location parameters comparison (Propane)

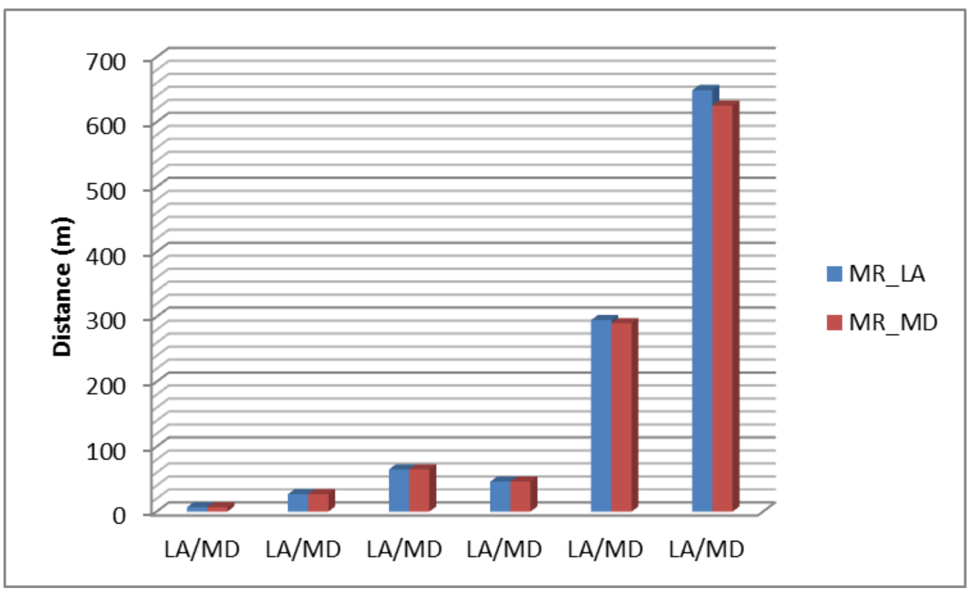

Figure 10. Dispersion location parameters comparison (Mixed Refrigerant)

From the results it is possible to identify that the variation on the dispersion distances based on the ambient conditions for each location would not represent a substantial impact.

7.3 Results representation on GIS

The main intention of using GIS for the representation of the results was to minimize the gap between the technical safety aspects (such as flammable dispersions) and the applicability of the results in a real world environment. First it is required to understand why the LNG terminals are located at those particular cities.

From the following map, it is possible to identify the large concentration of tight gas plays in Texas, Louisiana, Pennsylvania, and West Virginia (considering just those that have influenced the construction of LNG Terminals).

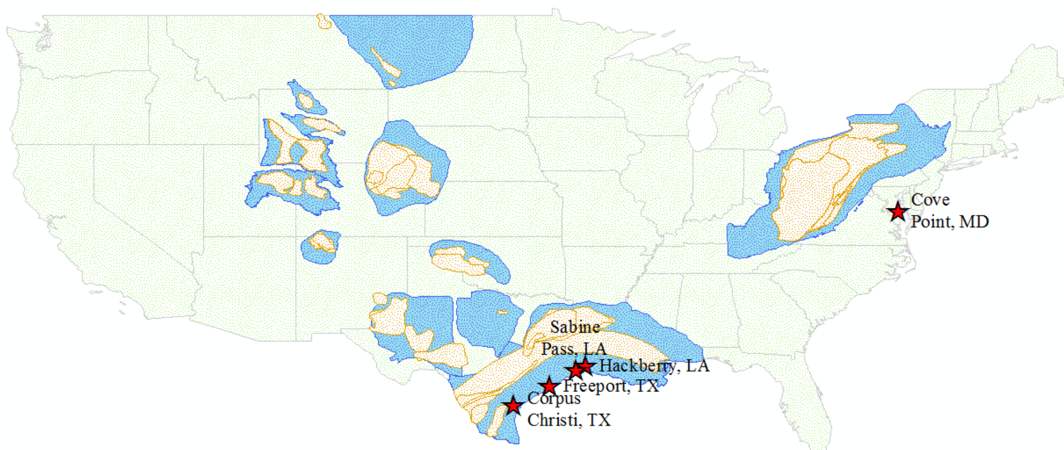

Figure 11. Approved LNG export terminals

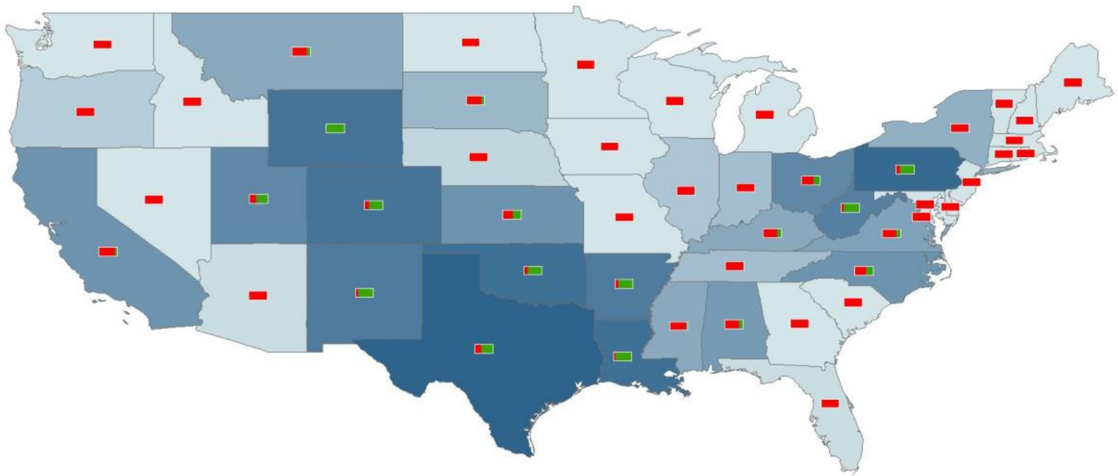

Figure 12. Natural gas consumption-production by state

Based on the information provided by the Energy Information Administration (EIA), it is possible to understand the relation between the consumption and production of natural gas by each state. Texas and Pennsylvania are the states with greater relation production-consumption. Cove Point LNG terminal is the facility that provides the opportunity for exporting LNG to the north east states.

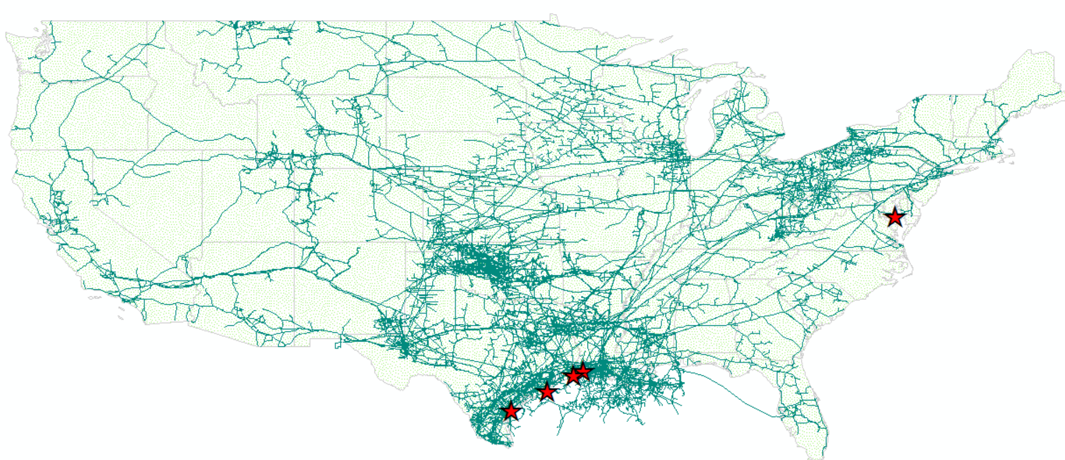

Figure 13. Interstate natural gas pipeline network

The pipeline density is highly concentrated at Texas and Louisiana. Several oceanic pipelines are connected to the offshore wells.

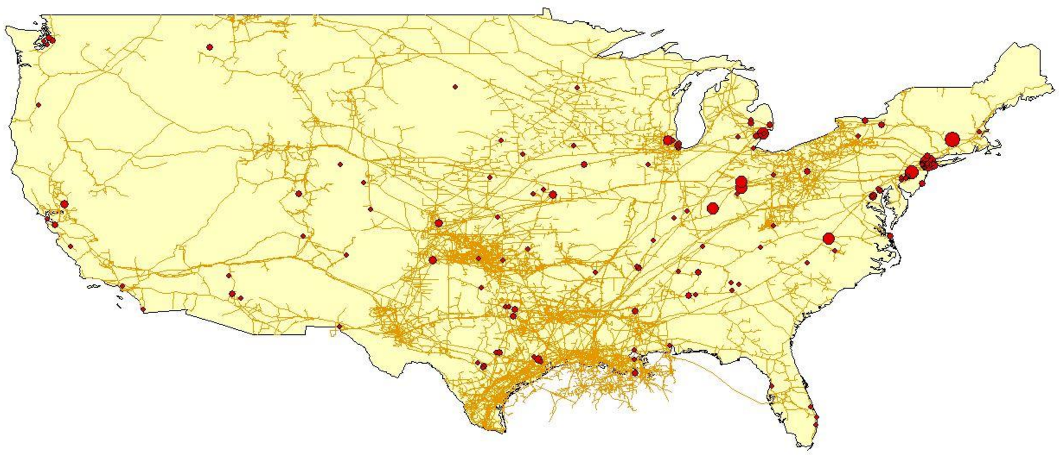

Figure 14. Accidents 2015 interstate natural gas pipeline network

During the 2015, the interstate natural gas pipeline accidents that presented a greater number of fatalities were located at the northeast region.

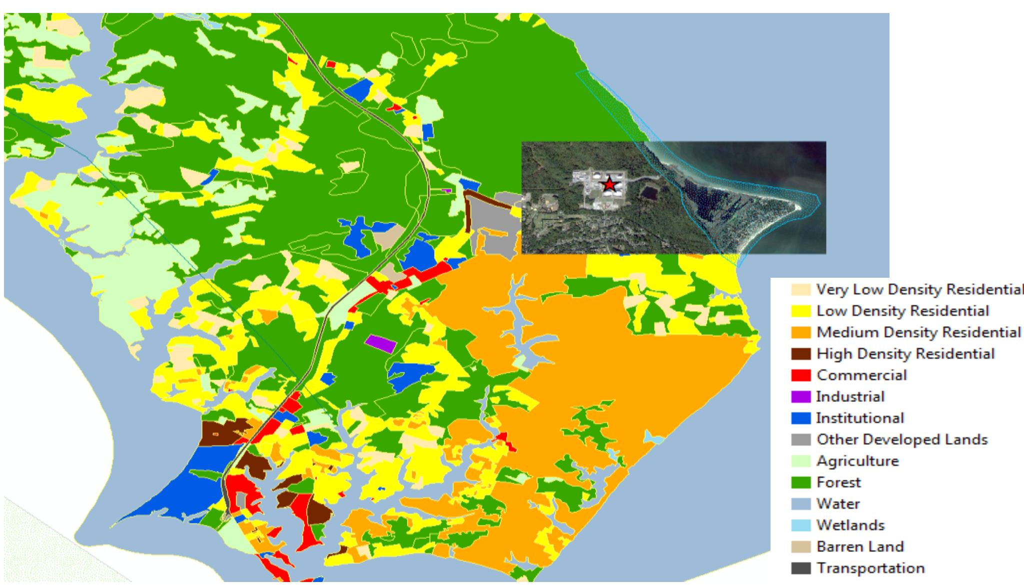

Figure 15. Cove Point, Maryland LNG terminal

Figure 16. Cove Point dispersion analysis

Figure 17. Sabine Pass dispersion analysis

Based on the vapor cloud dispersion calculations, it was possible to identify that the Cove Point facility may affect the nearby populated areas.

The integrated information related to areas under flooding hazards, population density, and natural gas pipelines might be helpful for assessing the potential negative consequences that might affect the LNG terminals.

8. CONCLUSIONS

8.1 Conclusions

The parameters established by the NFPA 59A for the assessment of exclusion zones provided the maximum downwind distances, in contrast with the parameters proposed for coastal areas. The results showed that a difference in wind speed of 0.5 m/s might be neglected. No radical changes were found between the NFPA parameters and those established by Crowl and Louvar for a potential worst case scenario.
Although this may represent that the results for the exclusion zones are overestimated, the nearby population has less chances for being affected by an accidental release of flammable materials.

The most critical event evaluated was related to the mixed hydrocarbon refrigerant. Based on the results for vapor cloud dispersion, and the dimensions of the potential facilities, the LFL is allowed to transport hazardous material beyond the facilities' boundary limit.

The most influential parameter was identified as the wind speed. The effects of a high wind speed may contribute with a faster dilution of the vapor cloud. Therefore, the estimation of the overall negative consequences would be inferior for average coastal areas, than those assessed for more calm ambient conditions.

Two different terminals were assessed for seven scenarios related to liquefaction and regasification terminals. The results shown no major variability when the relative humidity and ambient temperature differ from one facility to another one.

Although each LNG terminal might be designed for the specific characteristics of the natural gas received at the inlet pipeline, this analyzes represent an opportunity for getting a preliminary idea of the consequences that the plant would generate.

The integration of heavier hydrocarbons such as propane undeniably represents an increase of the potential negative outcomes. The modification of the existing LNG import facilities, will require a thoroughly analysis in order to minimize the results of an undesired event.

Evidently the complexities in terms of hazardous materials, and more processing equipment allow us to affirm that LNG export terminals represent a more challenging scenario.

8.2 Future work

In order to evaluate the potential damages on the facility due to an explosion, as the one occurred in Skikda, Algeria, it is necessary to find a simplified method for analyzing the congestion zones and its subsequent blast overpressure effects.

The integration of GIS material will allow the understanding on a bigger portion of the whole LNG chain. Information regarding the allocation of the pipelines in relation with the population proximity should be studied.

Also, GIS might be useful for analyzing the ship cargoes potential consequences. These types of ships, in some cases must sail across dense populated harbors. It would be interesting to analyze the potential benefits for using FPSO instead of onshore terminals.

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